TRANSFORMERS FOR OFFSHORE MULTI MEGAWATT TURBINES : DISCUSSION ON SPECIFICATIONS, SAFETY AND ENVIRONMENT

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Summary

This paper discusses dry-type transformers, conventional oil-filled transformers based on the cellulose mineral oil insulation system and new insulation systems for transformers used in wind turbines. The performance and functional specifications of liquid-filled transformers are explained. The reliability, safety and fire behaviour of dry-type transformers versus high temperature liquid-filled transformers is presented [1]. The safety and environmental impact of different types of liquid-filled transformers is discussed.

1. Introduction

The growing importance of renewable energy has been put on the agenda of many European and global (e.g. G8 summit) meetings. They all agree that efforts must be made to increase the share of renewable energy sources (RES) in global energy use by increased commitment to stimulate further development of offshore wind energy and next generation of wind turbines. [2]

The European RES-E Directive 2001/77/EC aims to increase the share of electricity from renewable energy sources from 14% in 2000 to some 22% by 2010. The drive behind this action plan is the recognition that wind energy will highly contribute to securing Europe's independent energy supply, reduce greenhouse gas emission and improve environmental protection.

2. Maximise the value of wind energy

In order to maximise the value of wind energy, several actions can be taken:

2.1 Harvest the resources

Since the power in the wind is proportional to the cube of wind speed ($P \sim v^3$), a 20% higher wind speed means over 70% more wind energy content. This is one of the key aspects when assessing the economic feasibility of a wind project.
The use of an update "wind atlas" is an essential tool in selecting the high potential wind energy sites and in selecting the most appropriate wind turbine in power, height and rotor diameter. Wind projects are moving from inland to costal areas (near-shore) and further to offshore locations.

2.2 Upscaling the wind turbine

While for many years wind turbines were installed with rotor diameters of 60-90m and ratings below 2MW, recent developments lead to the installation of trial units having rotor diameters up to 126m and 6MVA output power. Examples are the 5MW Multibrid, the 5MW Repower and the 4.5-6MW Enercon. Turbine components, such as blades, gear box, tower, generator but also the transformer have to be upgraded to match these developments.

Drivers of the trend to increase wind turbine power are reduction of public perception (less towers and slower rotation) and minimisation of the installation cost (especially for offshore foundations and cabling).

2.3 Wind power plants

Wind farms with many multimegawatt turbines operate almost like conventional power plants. While reliable and controllable output, energy storage systems and grid connection and integration are issues that have to be (and will be) technically covered, there is also the aspect of the public acceptance of such large farms (the "not in my backyard" standpoint). Going offshore and preferably at least 10km from the coast, is one of the most predictable solutions.

Up to a few years ago, dry-type transformers have been installed in the vast majority of wind turbines because of their good fire behaviour and compact dimensions. However, liquid-filled transformers with fire retardant fluid have recently been developed for the multi-megawatt turbines because their performance and reliability makes them particularly suited to such applications. The non-transformer industry considers these transformers as a high risk for fire and environmental issues and perceives dry-type transformers as perfect. However, seen what happened at Horns Rev and Middelgrunden, this is not a black and white situation. Modern decision-taking, and especially for offshore applications, must now account for not only the fire aspect, but also for other issues such as overall performance at severe operational conditions, reliability at increased ratings and voltages, energy losses, maintenance, environment (including end-of-life recycling).

Research was conducted to investigate the fire behaviour of both dry-type and liquid-filled transformer technologies, as well as the environmental and design impact of alternative cooling fluids.

2. Specifications of transformers for offshore wind turbines

2.1 Insulating system specifications

The fundamental difference between the liquid-filled and dry-type transformer technologies is the electrical insulation medium, air/resin and paper/liquid insulation respectively. The conventional liquid immersed transformer uses cellulose and mineral oil, whereas the advanced technology referred as SLIM®, uses a high temperature aramid insulation material called NOMEX® and a silicone liquid. The insulation structure also contributes to heat management and mechanical integrity.

These insulation materials were selected on basis of reliability, performance, safety and environmental concerns. Especially the liquid receives a lot of attention. Mineral oil such as used in conventional transformers is replaced by silicone liquid for its high fire and flash point (>300°C) as well as for its environmental friendliness. This means that silicone fluid does not react with the environment and degrades slowly in natural products. This is tested and approved by European legislation.

A further improvement in environmental behaviour can be obtained by using fully bio-degradable liquids. Again according European requirements, more than 65 % of the liquid must be degraded in 28 days. Esters, both natural and synthetic, can be used for this purpose. Natural esters are now being used in limited numbers of prototype transformers and trial series, but a lot of questions on life time behaviour remain unanswered. The synthetic ester known as MIDEL®7131 is already in use for more than 20 years and has a proven track record.

The authors investigated extensively and carefully the use of this synthetic ester for introduction in the high temperature wind turbine transformers (WTGT) of the SLIM® family. The liquid can be optimally used in combination with the high temperature NOMEX® insulation system to obtain the renown compactness and reliability of the SLIM® WTGT. This resulted in the developments of a new generation of compact transformers for offshore wind turbines called Bio-SLIM®.

2.2 Operating conditions

Going offshore means that the transformer will face very harsh environmental and functional operating conditions.

2.2.1 Cooling atmosphere

Transformers in offshore wind farms will be installed either on a platform at a certain level inside the tower, high up in the nacelle, or in a kind of container hanging under the nacelle. In each of these cases, the external transformer cooling medium will be outside marine air which is very humid, very salty and very variable in temperature. This air will pass the cooling elements or channels of the transformer in a direct natural way or forced via fans and conduits. Liquid-filled transformers with their steel tank having a surface treatment which can go as high as C5I+M, surpassing the highest ISO 12944-2 [3] classes, will hardly suffer from this corrosive environment. Dry-type transformers with their exposed windings are much more sensitive to condensation, electrical creepage, partial discharges, cracks, temperature variations and contamination. The only way to protect the dry-type transformer is to house it in a hermetic envelope equipped with an heat exchanger, an air-treatment unit (drying/filtering) and forced ventilation. A total concept which is costly, large in dimensions, consumes energy, and needs maintenance. In case the fans would refuse working (electronic controlled non-stationary components), the transformer and turbine have to be shut down.

The advantages of the robust, compact and naturally cooled KNAN liquid-filled transformer are obvious without further explanations. Only once the wind turbine generator (WTG) is rated 4MW and bigger, separate coolers start to become interesting since the heat generated by the transformer losses can be directed to a liquid-to-air exchanger allowing to dissipate the heat directly into the ambient instead of inside the tower or nacelle where it has to be removed by a second cooling system.

2.2.2 Vibrations

Transformers installed in or under the nacelle are victim to considerable vibrations due to the wind load hitting the wind turbine. Again, liquid-filled transformers designed for rough mechanical stresses prove to have a higher reliability to withstand shocks and vibrations than the cast coil windings, simply clamped between rubber pads.

The corrugated tanks of liquid-filled transformers will have vertical and horizontal reinforcements to reduce vibration and resonance. The core/coil assembly (also called “active part”), will be highly clamped and secured in the tank, restricting any movement in any of the three dimensions. Static and dynamic vibration tests on SLIM® transformers have shown that the frequency pattern which is typical for WTG (mainly in the low frequency range between 5Hz and 250Hz), hardly trouble these liquid-filled transformers.

2.2.3 Voltage variations

Compared to dry-type transformers, the superior electrical character of NOMEX® insulation combined with a high quality impregnation with a Class K liquid dielectric, makes this insulation system less sensitive to the high electrical stresses imposed by the frequent switching in-and-off, the transferred overvoltages and the transient surges. One typical feature of liquid-filled transformers is the ability to regenerate a local discharge. While in cast coils the partial discharges are captured inside a void in the resin and continues to deteriorate the insulation, a liquid based insulation system will automatically send new liquid to the fault area to replace the damaged one.

2.2.4 Load variations

The superior thermal character of NOMEX® combined with a high temperature liquid will hardly see any thermal aging under typical working conditions, including overloads, overtemperatures and reduced cooling efficiency.

3. Development of the Bio-SLIM® transformer

3.1 Selection of the cooling liquid

As mentioned in clause 2.1, the evolution towards offshore wind farms and the need for fully-biodegradable liquids with no adverse toxic environmental or aquatic side-effects, made Pauwels decide to do some research in the use of esters for these typical applications. While several alternatives are available on the market, the currently most renown synthetic ester is MIDEL®7131 by M&I Materials Ltd based in the UK.
MIDEL®7131 has proven transformer performance up to at least 135MVA and 238kV and became well-established in the field of transformer technology excellence.

The three industrial leaders DuPont, M&I Materials and Pauwels combined their know-how to create the Bio-SLIM® transformer. See a 2.3MVA/20kV Bio-SLIM® transformer in the photo below. We painted it blue to distinct it from SLIM® and to link it to marine and water applications.

3.2 Synthetic ester MIDEL®7131

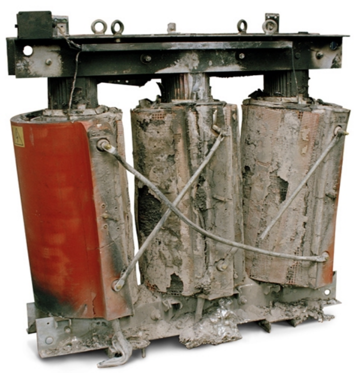
MIDEL®7131 is the preferred dielectric fluid for transformers in environmentally sensitive locations. The Federal German Office for the Environment has classified it as “non-water-hazardous” and it is recognised as “readily bio-degradable” according to OECD standards. Its electrical stability allows it to be operated at voltages above the medium voltage range (>36kV).
Developed by M&I Materials Ltd. originally as an environmentally friendly replacement for pcb, MIDEL®7131 transformer fluid is fully recyclable, is halogen-free, has a Class K (>300°C) fire point and excellent dielectric properties. As a synthetic ester, it complies with IEC 61099 [4].

3.3 Fire behaviour

Seen the high importance of the fire behaviour in the overall risk assessment of transformers used in indoor installations, we summarize the results of the comparative full scale fire test we performed on a 1MVA cast resin transformer and a 1.1MVA SLIM® transformer at Ineris, France in 2004 [1].
The test conditions were based on standard CENELEC HD 464 S1 for dry-type transformers.
The transformers were placed in a thermally aggressive environment characterised by a fire from alcohol below the transformers for 20 minutes and radiation from 2 panels along the side walls for 40 minutes with a heat input of 30kW/m².

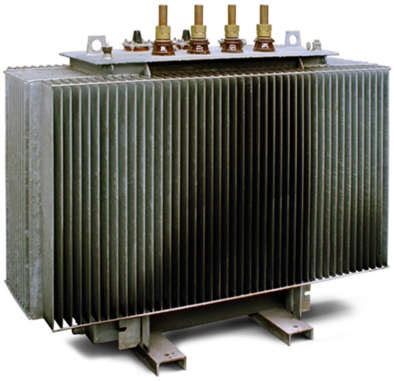
Performance of the dry-type transformer

After initiating the fire and the radiation panels, the transformer generated combustion and smoke after 6 minutes. The temperature of the external fire was 400°C whereas the temperature on the central winding reached 870°C after 8 minutes. The temperature dropped slowly to 700°C after radiation was stopped and dropped further to 400°C leaving the transformer burning on its own for more than an hour. The temperature on the top yoke reached more than 800°C, even after the external heat was switched off. The emission of gas (mainly CO) reached 720ppm after 9 minutes and decreased slowly to 350ppm. The transformer was a total-loss (see photo below).



Performance of the silicone filled SLIM® transformer

The heat generated by the fire and the panels resulted in external temperatures up to 600°C and an internal temperature of 260°C. Due to thermal expansion of the liquid, the pressure rose to 1.6bar. However, this pressure rise was not sufficient to burst the tank.
The transformer did not contribute to the external fire. On the outside of the transformer, no significant damage was noted (see photo below). After replacement of the gaskets of the bushings, the transformer was again ready for service.



Performance of a MIDEL®7131 filled transformer

The above described tests involved a silicone fluid-filled SLIM® transformer. A similar test has been done in the late eighties on a MIDEL®1731 filled 630kVA BBC transformer. The test was performed at the fire test room of the Allianz Versicherungs-AG [5]. The transformer withstood a 50 minutes external wood fire. While the outside temperature reached 420°C, the top liquid temperature did not pass 205°C. The pressure relief valve opened at 0.3 bar, but the gasses could not be ignited. The tank did not leak at any point, the MIDEL®7131 filled unit did not contribute to the fire incident.

3.4 Electrical specifications

Initially for design safety, we assumed esters would dielectrically behave as silicone fluids and we used the same electrical clearances, insulation configuration and creepage. However the market interest for esters forced us to research design optimisation in order to be able to improve the commercial position of ester-filled transformers. Laboratory tests on test coils and full scale models proved that the electrical performance of esters is much more similar to that of mineral oil than to that of silicone fluid.
One important difference was found in the partial discharge behaviour of the HV-windings. This is linked to the viscosity of esters being higher at room temperature than that of the other dielectric liquids. This means that the designing and the conditioning of MIDEL®7131 and of the filling process also need special measures in order to improve the impregnation of the solid insulation (whether cellulose or NOMEX®) and its withstand voltage.
At the same time, the electrical stability of MIDEL®7131 allows it to be operated at voltages above the medium voltage range (>36kV). This is a real advantage for offshore applications where transforming the turbine output voltage directly to 52-72kV may eliminate the power substation on the central platform, or save a lot in the turbine-to-grid cable connections.

3.5 Thermal specifications

The thermal performance of esters is in between that of mineral oil and silicone fluid. Heat run tests were done at 80%, 100% and 120% of loading on 2.3MVA/20kV Bio-SLIM® transformers we build for one of the leading wind turbine manufacturers. The numerous thermocouples we placed in and around the windings showed a thermal profile which was better than expected. The temperature rises in MIDEL®7131 filled transformers are just slightly higher than in mineral oil conditions.

Continuous top liquid operating temperatures for liquid filled transformers are limited to 100°C in mineral oil, 130°C (to 140°C if hermetically sealed) for esters and 155°C for silicone fluid [6]. Since the bulk and top liquid temperatures are limited by the accessories such as gaskets and bushings, the Bio-SLIM® units need to be slightly derated in winding temperature compared to the SLIM® units, not for the NOMEX® but for the liquid in contact with the winding hotspot.

Esters are hygroscopic and tend to absorb a lot of moisture, however while keeping their dielectric strength high. The solid insulation will therefore suffer less of thermal aging if this process occurs in a hermetically sealed transformer which is the case of Bio-SLIM®.

The thermal expansion coefficient of ester (0.00075) is close to that of mineral oil (0.00076). Silicone fluids expand some 37% more (0.00104). This means that tank flexibility and internal pressure are almost equal for ester and mineral oil.

3.6 Material compatibility

Esters have no problems with material compatibility. Identical materials can be used as in conventional mineral oil filled transformers. The restrictions of combining silicone fluid with certain types of gaskets, glues, varnishes, enamels, paints, … are no issue with esters.

4. Comparison table

Thanks to performing more identical to mineral oil, Bio-SLIM® transformers will allow for the most compact design possible.

	Cast Resin	Conv. Class K	Bio-SLIM®
Po	3900 W	2350 W	2350 W
Pk 75°C	20700 W	18000 W	16000 W
Pk 120°C	23000 W	-	18000 W
Uk	6 %	6 %	6 %
Lw	76 dB(A)	71 dB(A)	71 dB(A)
Length	1950 mm	2085 mm	2160 mm
Width	1310 mm	1150 mm	760 mm
Height	2190 mm	2150 mm	2125 mm
Volume	5.60 m³	5.16 m³	3.44 m³
Fluid mass	-	1210 kg	840 kg
Total mass	5250 kg	6000 kg	5040 kg
Top liquid	-	50 K rise	70 K rise
Avg winding	90 K rise	55 K rise	110 K rise

Notes:

- Cast resin transformer having reduced losses
- Designs suited for 50°C ambient temperature
- Height without wheels

5. Conclusions

As demonstrated above, one more model is added to the family of liquid-filled transformers highly suited for offshore wind turbines and environmental sensitive applications.
While a WTGT takes only some 3% of the total wind turbine installation, it is one of the critical components next to the turbine, generator, gear box (if any) and converter power electronics. If the transformer fails, power generation stops. Some of the earlier service failures of series of WTGT may have been caused either by quality compromises with negative impact on reliability due to prices being driven down too low, or by insufficient understanding of the specific operating conditions.

Today it is possible to reduce the risk for failures and their impact on safety and environment to an absolute minimum. It is up to the final user to evaluate the added values of each of the products for each of his projects. The Bio-SLIM® transformers opened the door for using liquid-filled transformers in the nacelle or the base of offshore multimegawatt wind turbines, connected to grids of 36kV and above. One should value the WTGT for that performance and invest in a safe and highly reliable top quality product.

6. Acknowledgements

The authors thank the NOMEX® team of DuPont De Nemours, Switzerland, the MIDEL®7131 team of M&I Materials Ltd, UK and Enercon GmbH, Germany for their co-operation.
Technical Editor: Mario Desmit, Pauwels International N.V.

7. References

[1] Performance and fire behaviour of step-up transformers in wind turbines, J.Declercq & Raymond Van Schevensteen, Pauwels International, EWEC London, 2004

[2] Prioritising Wind Energy Research, Strategic Research Agenda of the Wind Energy Sector, EWEA, July 2005

[3] ISO 12944-2 : Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 2 : classification of environments.

[4] Standard IEC 61099 : Specifications for unused synthetic organic esters for electrical purposes.

[5] Allianz Risk Service – Special Issue – Allianz Fire Protection Service – Fire test on a transformer filled with MIDEL®7131 – ref. F/ABS 1465/6 (0/00) 5.3.88

[6] Standard IEC 60076-14 : Design and application of liquid-immersed power transformers using high-temperature insulation materials.